

Modeling the time-resolved quasi-periodic oscillations in AGNs

Tapas K. Das^{1*} and B. Czerny^{2†}

¹*HRI, Chhatnag Road, Jhansi, Allahabad 211 019, India*

²*Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland*

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ABSTRACT

Observation of the bright Seyfert 1 galaxy RE J1034+396 is believed to demonstrate a drift of the central period of the Quasi Periodic Oscillation (QPO) linearly correlated with the temporary X-ray luminosity. We show, using a specific scenario of the oscillation mechanism in black hole accretion disc, that modeling such correlated trends puts very strong constraints on the nature of this oscillation and the characteristic features of the hot flow in Active Galactic Nuclei (AGN). In our model, QPO oscillations are due to the oscillations of the shock formed in the low angular momentum hot accretion flow, and the variation of the shock location corresponds to the observed changes in the QPO period and the X-ray flux. In this scenario, change in the shock location caused by perturbation of the flow angular momentum is compatible with the trends observed in RE J1034+396, whereas the perturbation of the specific flow energy results in too strong flux response to the change of the oscillation period. Using a complete general relativistic framework to study the accretion flow in the Kerr metric, we discuss the role of the black hole spin in the period drift. Future missions are expected to bring more active galaxies with time-resolved quasi-periodic oscillations so similar quantitative study for other QPO scenarios will be necessary.

Key words: accretion, accretion discs – black hole physics – hydrodynamics – shock waves – galaxies: active – galaxies: individual: RE J1034+396

1 INTRODUCTION

The details of the accretion flow pattern in AGN are far from being well understood. One particular issue of profound interest in this regard is to predict the location of the hard X-ray emitting region in such flows. Spectral analysis of the present data is yet to provide any unanimously accepted solution to this long standing question. Although the presence of the relativistically smeared iron line imposes certain constraints (e.g. Fabian et al. 2002, Miniutti et al. 2007, 2009, Schmoll et al. 2009, Niedzwiecki & Zycki 2008, Niedzwiecki & Miyakawa 2010; for a review, see e.g. Miller 2007), the combined effects of the warm absorber and the reflection are, however, difficult to disentangle (for a review, see Turner & Miller 2009).

Future space missions, like the Astro-H, New Hard X-ray Mission (NHXM), International X-ray observatory (IXO), however, will provide new opportunities to address this issue. Several related proposals have already been put forward, e.g., the direct reverberation mapping for the iron

line (Armitage & Reynolds 2003, Goosmann et al. 2007). Indications for some strong temporary features have been, also for example, observed in the present X-ray data (see, e.g., Iwasawa et al. 2004, Ponti et al. 2004, Miller et al. 2006, Turner et al. 2006, Miniutti et al. 2007, Tombesi et al. 2007).

In this work, we propose a novel theoretical approach to address this issue, based on the study of the expected properties of the QPO in AGN. So far only one AGN showed indisputably a QPO episode with a period of 3733 s (Gierlinski et al. 2008, Middleton et al. 2009), and it corresponds to the 67 Hz QPO observed in GRS 1915+105 (Middleton et al. 2010). The detection was highly significant, and further study of the QPO time evolution during the single observation was possible with the use of the wavelet approach (Czerny et al. 2010). A few other tentative detections have also been suggested (e.g. Papadakis & Lawrence 1993, Iwasawa et al. 1998, Fiore et al. 1989, Vaughan & Uttley 2005, Lachowicz et al. 2006, Espaillat et al. 2008, Lachowicz et al. 2009), although most of them were later questioned as being only due to the red noise (see Espaillat et al. 2008 for specific references). However, further observations with current and future instruments will come up with high quality X-ray light curves of many more AGNs, so even if the duty cycle

* tapas@mri.ernet.in

† bcz@camk.edu.pl

for high-frequency QPO in AGN is as low as that observed for the galactic black hole candidates, we expect to detect several QPO episodes (see e.g. Vaughan & Uttley 2005), and the light curves will be of sufficiently high quality to study time-resolved frequency drift in a single QPO episode. The signature of such a drift is believed to be already observed using the XMM data for RE J1034+396 (Czerny et al. 2010), and the corresponding period modulation is accompanied by the proportional change in the flux. In this work we show that the knowledge of the specific period-flux relation provides a good test of the QPO mechanism.

2 MODELING THE QPO

The characteristic features of the QPO observed in the galactic and the extra galactic sources indicate that such oscillations are a diagnostic of the accretion processes in the inner region of the black hole accretion discs. Direct analysis of the observational data shows that the high frequency QPO phenomenon appears only in a special spectral state - the steep power law state, referred also as very high state, but the dynamical QPO mechanism and the accretion flow pattern in this state are unknown. Several scenarios of the QPO origin are under consideration. One of the possibility is that QPO may be produced as a result of the oscillation of the shocks formed in hot accretion disc (Molteni, Tóth & Kuznetsov 1999, Okuda, Teresi, Toscano & Molteni 2004, Gerardi, Molteni & Teresi 2005, Okuda, Teresi & Molteni 2007, and references therein). Such shocks may form when the angular momentum of the inflowing material is low, and the role of viscosity unimportant, while they are not expected in ADAF-type solutions (see e.g. Narayan et al 1997) where the angular momentum is only slightly sub-Keplerian and viscosity plays the dominant role in the inflow.

Based on the assumption of the fine tuning of the inflow and the cooling parameters of a multi-transonic black hole accretion, time dependent simulation work (see, e.g., Molteni, Sponholz & Chakrabarti 1996) revealed that for a certain range of the initial boundary conditions, the radial oscillation of shock about their mean steady state location appear and they cause the quasi periodic variation of the luminosity emerging out of the post shock accretion flow (see also Giri et al. 2010 for more recent numerical shock oscillation results). The frequency of such shock oscillation was shown roughly equal to the post shock advection time scale. This mechanism may work if the whole inflow is optically thin or we have a two phase medium, with the hot accreting corona dynamically decoupled from the underlying cold disk. We adopt and test this scenario in our paper.

Since the post shock dynamical profile is essentially determined by the shock location (strength of the gravitational field) and shock compression (reduction of the dynamical velocity due to the shock), such time scale effectively depends on some function of the shock location r_{sh} and the shock compression ration R_{comp} as evaluated using the stationary solution (see, e.g., Das 2002, and references therein, for details of the calculation of r_{sh} and R_{comp} for a generalized multi transonic disc model). Hence from the theoretical front, the QPO frequency can reasonably be approximated by solving the stationary set of equations governing the axisymmetric flow of hydrodynamic multi-transonic shocked

accretion flow around astrophysical black holes (Chakrabarti & Manickam 2000, Das 2003, Das, Rao & Vadawale 2003, Mukhopadhyay, Ray, Dey & Dey 2003, Mondal 2010). In this work, we follow Das (2003) and Das et al. (2003) to evaluate the QPO frequency, which will be based on the assumption that the low angular momentum hot inflow develops a shock, and the QPO phenomenon represents the shock oscillation. To accomplish such task, one needs to self consistently determine the location of the standing shock as well as the compression ratio at the shock location. Both these variables are determined by three initial boundary conditions, the specific flow energy \mathcal{E} (also known as the Bernoulli's constant), the specific angular momentum λ and the adiabatic index γ of the flow (see, e.g., Das 2002 and Das, Bilić & Dasgupta 2007, and references therein, for the full details of such shock formation mechanism for the accretion flow under the influence of the pseudo-Newtonian black hole potential of Paczyński and Wiita 1980, and for full general relativistic flow analyzed in the Schwarzschild metric, respectively).

One can also compute the QPO frequency in the full general relativistic framework, by considering the low angular momentum axisymmetric flow in the Kerr metric. r_{sh} and R_{comp} will then be determined by four parameters, $\mathcal{E}, \lambda, \gamma$ and the Kerr parameter a , see, e.g., Das & Czerny 2009 and Barai, Chakraborty, Das & Wiita 2009 for details of such calculations in the Kerr metric. Hence the most general shocked accretion flow, which will be used in this work to calculate QPO and the related quantities, are characterized by four parameters $[\mathcal{E}, \lambda, \gamma, a]$.

The aforementioned four parameters may further be classified into three different groups, according to the way they influence the fundamental features of the accretion flow. $[\mathcal{E}, \lambda, \gamma]$ characterizes the *flow*, and not the space time (since the accretion is assumed to be non self gravitating in our work, which is a common practice in the existing literature), whereas the Kerr parameter a exclusively determines the nature of the space time, and hence can be thought as some sort of ‘inner boundary condition’ in qualitative sense (since the effect of gravity is determined within the full general relativistic framework only up to several gravitational radius – beyond a certain length scale, it asymptotically follows the Newtonian regime). Out of $[\mathcal{E}, \lambda, \gamma]$, again, $[\mathcal{E}, \lambda]$ determines the dynamical aspects of the flow, whereas γ determines the thermodynamic properties. Hence to follow a holistic approach, one needs to study the variation of the observed phenomena on all of these four parameters.

If the parameters governing the flow vary slightly in time due to variable outer boundary conditions the period of the QPO oscillation, as well as the overall X-ray emission will show a correlated drift in the similar pattern. We parameterize such phenomenon by assuming a sequence of quasi-stationary solutions, and quantify the characteristic trends of such a drift. If the energy or the angular momentum of the flow are perturbed, the position of the shock, and the corresponding frequency of the shock oscillation and the radiation flux will then be altered. We calculate them in the following way.

The period of the oscillation is calculated from the formula

$$P_{QPO} \propto P_K(r_{sh})R_{comp}, \quad (1)$$

where $P_K(r_{sh})$ is the Keplerian period at the position of the

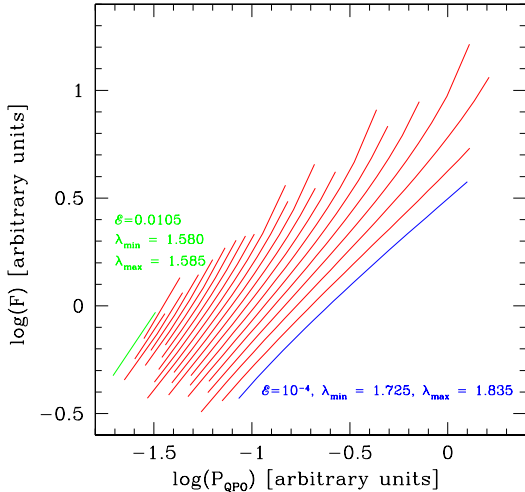


Figure 1. The logarithmic plot (in arbitrary units) of the flux vs. period relation for a fixed specific energy \mathcal{E} , and variable angular momentum, λ , for a polytropic index $\gamma = 4/3$. Not all the parameter region is covered since shocks form only for a certain range of \mathcal{E} and λ , for a given γ . The value of the specific energy as well as the maximum and the minimum value of the specific angular momentum for which the shock forms are shown for the leftmost (green line in the electronic version of the manuscript) and the rightmost (blue line in the electronic version of the manuscript) curve.

shock location. The compression term increases the oscillation period since the oscillations are not strictly dynamic but due to the coupled dynamical/thermal evolution, as shown (both analytically and numerically) by Molteni et al. (1996).

The X-ray flux attributed to the shock may be approximated as

$$F \propto 2\pi r_{sh} H_{flow} c_s^2, \quad (2)$$

where the sound speed, c_s , as well as the flow thickness (disc height, which itself is a complicated function of the sound speed and other accretion parameters, see. e.g., Das 2002 and Das & Czerny 2009 for the exact expression for the H_{flow} for pseudo-Newtonian and full general relativistic accretion flow, respectively) is measured in the post-shock configuration. The width of the shock depends on the microscopic physics and we assume it is constant for all our models, so we do not introduce it here as a specific additional parameter.

The numerical value of the proportionality constant for Eq. (1) and Eq. (2) are unimportant since we are interested in testing the expected correlations between the radiation flux and the QPO central period in log-log space. Predicted trend can directly be tested against the observed data.

3 RESULTS

Adopted scenario of the QPO mechanism in the form of shock oscillation in a hot axisymmetric low angular momen-

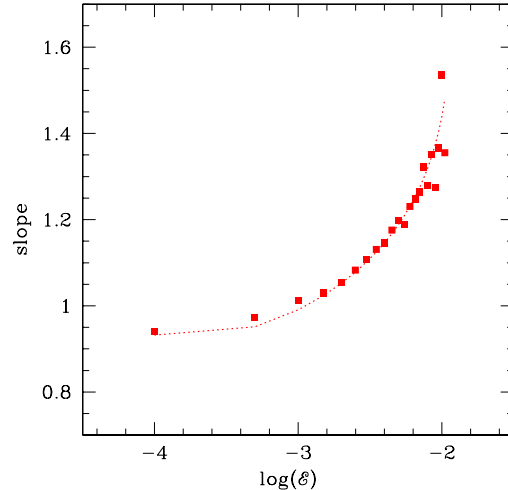


Figure 2. The slopes of the logarithmic dependence of the flux vs. period relation for a fixed specific energy \mathcal{E} , and variable angular momentum, λ , for a polytropic index $\gamma = 4/3$.

tum flow allows us to connect the expected relation between the X-ray flux and the central period of a QPO signal in a single AGN.

We first address the issue in the pseudo-Schwarzschild framework, by using the Paczyński and Wiita (Paczyński and Wiita 1980) potential, and using the similar kind of flow geometry as described in Das, Rao & Vadawale 2003. Hence the flow is essentially governed by $[\mathcal{E}, \lambda, \gamma]$ for this case. We study the quasi-stationary response of the average flux to the forced change in the QPO period. The stationary solution is specified by two dynamical parameters (specific flow energy \mathcal{E} and angular momentum λ), which are determined by the outer conditions in the flow which can vary with time. The solution is characterized by the adiabatic index γ as well, as described in §2.

We consider two types of perturbations corresponding to the aforementioned dynamical parameters $[\mathcal{E}, \lambda]$ separately.

First we fix the specific energy (i.e. the Bernoulli constant) and study the effect of the change of the angular momentum of the flow. Such a perturbation can appear if the angular momentum of inflowing plasma at a given radius changes with time without any significant corresponding change in the flow temperature. The dependence of the flux on the QPO period is shown in Fig. 1. Each curve corresponds to a fixed Bernoulli constant, \mathcal{E} , and the angular momentum varies along the curve, increasing from the left to the right of the figure. The curves are almost straight lines in log plot, slightly steepening at the longest period. However, the overall trend is well represented with a straight line for shorter periods, so we calculate the line slope and give it in Fig. 2. The slope is flatter than 1 for small values of the Bernoulli constant and rises considerably above 1 for $\mathcal{E} > 3.0 \times 10^{-3}$.

The slope is only weakly sensitive on the adopted value

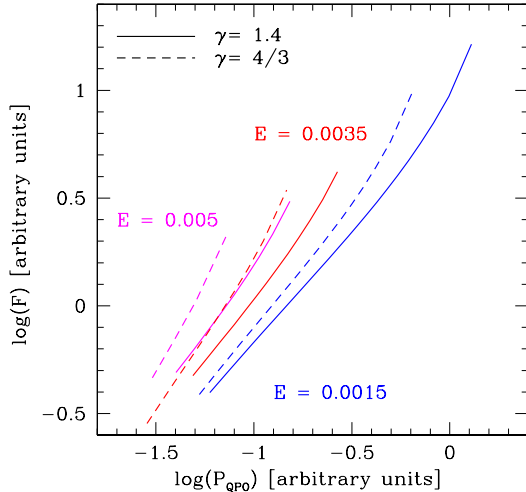


Figure 3. The logarithmic plot of the flux vs. period relation for a fixed value of specific energy \mathcal{E} , and variable angular momentum, λ , for three pairs of solutions for three different values of \mathcal{E} . Each pair is characterized by two different values of the adiabatic indices, $\gamma = 4/3$ (marked by the dashed curve) and $\gamma = 1.4$ (marked by the solid curve).

of the parameter γ . If lower value of the adiabatic index, e.g., $\gamma = 1.4$, is used, which is typically adopted for the partially ionized interstellar medium and for hot but magnetized ADAF (Advection-dominated Accretion Flow) plasma close to equipartition with the magnetic field (see, e.g. Esin 1997, Narayan et al. 1998), the slope becomes slightly steeper, particularly at high energies (see Fig. 3). Quantitatively, the slope increases from 1.03 to 1.13 for $\mathcal{E} = 1.5 \times 10^{-3}$, and from 1.20 to 1.58 for $\mathcal{E} = 5 \times 10^{-3}$.

We next study the case of the constant λ by varying the asymptotic value of the Bernoulli constant, \mathcal{E} . This means that the angular momentum of the flow at a given radius remains constant while the plasma temperature falls or rises. In this case the change of the flux correlated with the change of the QPO period is much more rapid (see Fig. 4). As before, we measure the slopes at the linear part of the log-log plot. The slopes are much steeper, 2.29 for $\lambda = 1.725$, increasing even further with an increase of λ . Thus the response of the flux is very sensitive to the nature and the characteristic features of perturbation involved. The range of the slopes of the flux-period relation as a function of the parameter λ is shown in Figure 5 as the set of red squares. Since in the case of constant λ the curvature is more significant than in the case of constant \mathcal{E} perturbations, in addition we also show slopes measured in the upper parts of every $\log F - \log P_{QPO}$ curve (blue circles) and the slopes just measures as a difference between the two extreme points on the curve (green triangles).

The two types of the perturbations thus differ significantly in the predicted slope in the flux-period relation. Perturbations which involve both the change of the specific

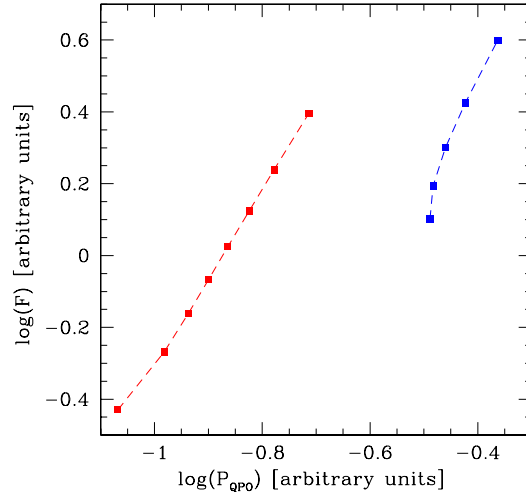


Figure 4. The logarithmic plot of the flux vs. period relation for a fixed angular momentum, λ , and variable asymptotic value of the Bernoulli constant, \mathcal{E} . Two sequences represent two values of λ : 1.725 (left curve, magenta coloured line in the online version) and 1.775 (right curve, blue coloured line in the online version), $\gamma = 4/3$.

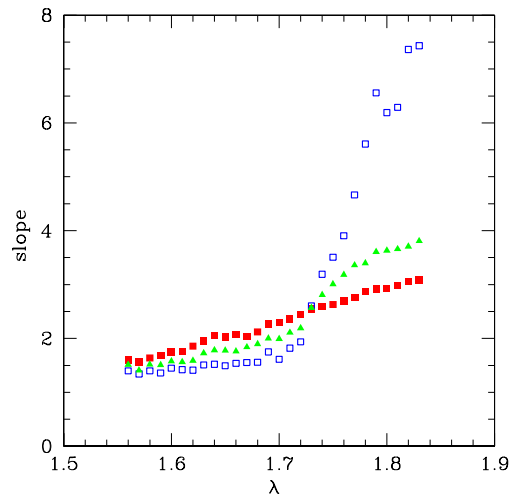


Figure 5. The slopes of the logarithmic dependence of the flux vs. period relation for a fixed angular momentum, λ , and variable Bernoulli constant, \mathcal{E} , for a polytropic index $\gamma = 4/3$ measured in the linear part of the relation (red squares), in the high period part (blue circles) and from the extreme points (green triangles).

flow energy and the angular momentum should show intermediate slopes between the two extreme cases.

Finally, we examined whether the results depend significantly on the spin of the black hole. Our basic model (Das et al. 2003) was developed for the Paczyński and Wiita (Paczyński and Wiita 1980) pseudo-Schwarzschild potential, well describing a non-rotating black hole. Therefore, to study the effect of the Kerr metric, we used more general flow equations, as described in detail by Das & Czerny (Das & Czerny 2009) which allows to determine the shock location and the flow parameters within a complete general relativistic frame work. We then use Eqs. 1 and 2 taking local flow quantities without any relativistic corrections for the outflowing X-ray flux. Three examples of the flux-period relation are shown in Fig. 6. The slope of this relation does not change with the Kerr parameter because the shock does not form very close to the horizon where the black hole spin has leading effects. The representative value of the specific flow energy (general relativistic Bernoulli constant), including the rest mass factor, is taken to be $\mathcal{E} = 1.0000044$ (similar figures can also be drawn for any other required value of \mathcal{E}), which is close to the lowest value used to construct Fig. 2, hence the direct comparison is possible. Of course the range of the frequencies has changed but this is relevant only if there is an accurate determination of the black hole mass involved in the process. The effect is due to the fact that the local properties of the flow do not strongly depend on the Kerr parameter at distances of $\sim 10R_g$, where the shock forms, and the flow parameters are measured. However, the global properties of the solutions do depend strongly on the Kerr parameter, as discussed in Barai, Chakraborty, Das & Wiita 2009 (see, e.g., figure 5 and 6 of this paper).

The model does not have any explicit dependence on the accretion rate, and does not imply any such constraints on inflowing material. This is valid as long as the accretion rate, and the flow optical depth are not too high. Our model does not include the effect of the radiative cooling on the flow dynamics, and this assumption breaks down for accretion rates of the hot inflow above a fraction of the Eddington rate, when the optical depth for the electron scattering is ~ 1 .

4 DISCUSSION

We study a shock oscillation scenario of the QPO oscillations suggested by Molteni et al. (1996) and later considered by a number of authors as described in the section 2. Within the framework of this model, thermal/dynamical oscillations of the shock correspond to the QPO frequency, and deviations from the shock location due to the change of the asymptotic values of the flow result in a correlated change in the QPO period as well as in the flux averaged over QPO period. The well specified model allows us to predict the slope of this correlated change of the period and the flux, which can be compared with the value directly obtained from the X-ray data.

There are also other mechanisms proposed for explanation of QPO: (i) Trapped pulsating modes with an inner disk/torus (e.g. Perez et al. 1997, Wagoner et al. 2001, Espaillat et al. 2008, Straub & Sramkova 2009), (ii) Temporary spots on the disk surface (e.g. Karas 1999, Schnittman 2005,

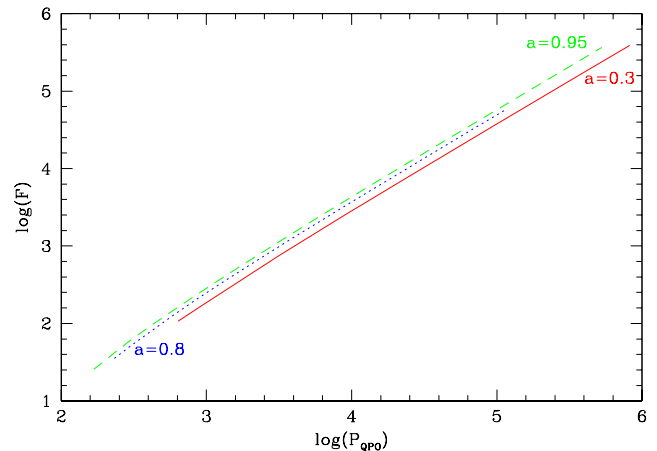


Figure 6. For complete general relativistic flow in the Kerr metric, the logarithmic plot of the flux vs. period relation for a fixed Bernoulli constant, $\mathcal{E} = 1.0000044$, and variable angular momentum, λ is shown. Three sequences represent three values of the Kerr parameter, $a = 0.3, 0.8$ and $a = 0.95$ respectively. The value of the adiabatic constant is taken to be $\gamma = 4/3$.

Bachetti et al. 2010), (iii) Epicyclic coupled oscillations in both vertical and radial directions from exact planar motions within a disk (e.g., Abramowicz & Kluzniak 2001, Abramowicz 2005, Horak et al. 2009; see also Stella & Vietri 1999), and (iv) Disk-jet magnetic coupling (e.g. Wang et al. 2007). Some of those models, like oscillations of the radiating tori, have in principle the required predictive power to give the expected flux-period relation but the computations are time consuming so single examples only are shown in the respective works. In other cases, like epicyclic coupled oscillations, the models do not contain yet the predictions of the X-ray emissivity. Shock oscillations can already be tested, although under some assumptions, and this issue will be addressed in Sect. 4.3.

4.1 Application to RE J1034+396

The QPO phenomenon was discovered in this source by Gierlinski et al. (2008). More detailed analysis of the same XMM data sequence by Czerny et al. (2010) based on wavelet analysis indicates that the QPO period shows a drift, which was accompanied by a change of the X-ray flux, with the index of the power law trend of 0.92 ± 0.03 . If this value is indeed representative for the QPO in this source, then it is consistent with predictions of the shock model in case of purely angular momentum perturbations, and the Bernoulli constant of order of $\mathcal{E} \sim 10^{-4}$ or lower.

Such perturbations seem to be more likely in the case of a turbulence in a magnetized plasma; magnetorotational instability (MRI; Balbus & Hawley 1991) in such a flow may lead to angular momentum redistribution without very significant heating/cooling of the plasma. However, at this moment no adequate simulations of the process are available. The MHD computations of the low angular momentum flow were performed mostly in 2-D approximation (Proga & Begelman 2003, Okuda et al. 2007, Moscibrodzka & Proga 2009), 3-D computations were done without the magnetic field (Janiuk et al. 2009), only Gerardi et al. (2005) performed 3-D MHD, but all those papers neglected dissipation. Some 3-D MHD do include radiative losses (e.g. Hirose, Krolik & Stone 2006, with subsequent applications) but those computations assume shearing box and almost Keplerian disk.

The energy constraint can be translated to the hot plasma temperature at the outer boundary, and the implied temperature is ~ 300 keV or lower, i.e. comparable to the electron temperature of the plasma considered in the coronal models of the origin of the X-ray radiation.

Both constraints are consistent with the likely global scenario of the accretion inflow in this object. The broad band spectrum of RE J1034+396 is dominated by the multi-color black body component (Puchnarewicz et al. 2001, Loska et al. 2004, Middleton et al. 2009), and additional the power law component is steep (Middleton et al. 2009). We identify this power law emission with low angular momentum accretion flow discussed in detail in the present paper. The fraction of energy emitted by the disk is much higher so the accretion goes preeminantly through this channel, and the accretion rate in the hot plasma is only a small fraction of the total accretion rate. The temperature of the plasma responsible for this power law emission cannot be determined observationally because the high energy cut-off is not seen, but the value of 300 keV mentioned above is thus consistent with the data. However, in the future the model should be further developed to include the radiative coupling between the two phases and to test the possible role of the dynamical (magnetic) coupling of the cold and hot flow using some simple parametric approach.

4.2 Prospects for further QPO detections in AGN with current and future experiments

As discussed by Vaughan & Uttley (2005), the exact estimate of the future QPO detections are not quite straightforward. Simple increase in the detector area will not help for a specific source if the QPO frequency happens to be in a frequency range dominated by the red noise. However, the actual detection of the QPO in RE J1034+396 shows that the detection is viable even now, with the XMM-Newton telescope, for a typical duration of an observation. The QPO with the period of ~ 1 hour detected in RE J1034+396 implies the expected periods in other AGN of similar order, or somewhat longer, if the black hole mass is larger. However, even shorter periods may be expected since the RE J1034+396 is an equivalent to 67 Hz QPO in GRS 1915+105 (Middleton et al. 2010), and in some other AGN we may see the frequencies corresponding to kHz QPO typical for other galactic sources. The only problem is that the number of lightcurves of this S/N quality is small, and with

the expected short duty cycle, confirmed by the absence of the QPO in the first part of the 2007 data as well as in whole 2009 data (C. Done, P. Lachowicz, private communications), the probability to pinpoint a source in the right state is low. Another source may show a QPO phenomenon in the XMM-Newton or Suzaku observation any time, but telescopes with bigger area like the proposed IXO mission would bring good S/N lightcurves for numerous AGN. Also other missions with smaller detector area but focused on extension of the detection towards harder X-rays may bring QPO phenomenon more effectively, since the QPO signal is more profound at higher energies (Middleton et al. 2009).

4.3 Applicability of the shock model to disk-dominated states

The dynamical model of the flow relies on the assumption of constant, low angular momentum. If the accretion flow is dominated by the standard disk, the model still applies to the coronal hot flow if the disk/corona coupling is negligible. Such sandwich disk/corona flow has been considered by several authors (e.g. Meyer & Meyer-Hofmeister 1994, Życki et al. 1995, Witt et al. 1997, Rozanska & Czerny 2000, Meyer et al. 2000, Mayer & Pringle 2007, Kawanaka et al. 2008, Liu & Taam 2009). On the other hand, the inner flow is likely to be dominated by the hot flow in the QPO state since no variations in the cold disk are seen in QPO spectra of galactic sources (e.g. Sobolewska & Życki 2006). Also QPO in RE J1034+396 are related entirely to the hot flow (Middleton et al. 2009). The assumption of bremsstrahlung cooling in the simulations performed by Molteni et al. (1996) has further been relaxed in recent hydrodynamical simulations performed by Giri et al. (2010) where it has been demonstrated that the oscillations appear even in the adiabatic case, essentially due to a possibility of a temporary backflow. In this case the radiation is a small perturbation to the dynamics of the flow and outgoing spectrum can be dominated by Comptonization, as observed in reality.

Calculation of the flow spectra is beyond the current model, as this would require determination of the electron temperature of the flow, and additional assumptions on the dissipation within the shock. We can only state that there is no basic discrepancy between our model and the observed spectrum fitted by Middleton et al. (2009). The fraction of luminosity in the hard power law tail coming from the hot flow is small, the exact value strongly depends on the adopted model as the decomposition of the X-ray spectrum into soft and hard components is not unique, and the hard X-ray slope changes with the model change from $\Gamma = 2.3$ to $\Gamma = 3.6$. The high energy extension of this tail is also not determined so the optical depth of the hard X-ray emitter is unknown.

4.4 Applicability of the study to Galactic Black Holes

Accretion processes onto black holes show amazing similarity across the very broad range of black hole masses from $\sim 10M_{\odot}$ Galactic sources to $10^{10}M_{\odot}$ bright quasars. However, the correlations studies here are not expected to apply to galactic sources under the present time resolution. The

observed correlation obtained for RE J1034+396 showed a period trend within a *resolved* single QPO episode, and the model presented here also aims to simulate such a situation. This QPO oscillation may be an analog of the 67 Hz high frequency QPO in GRS 1915+105 (Middleton & Done 2010). High frequency QPOs in Galactic sources are, at present, unresolved within their dynamical timescale, so the observed correlations, if any, would imply secular trends corresponding to a major rearrangement of the flow geometry in a long viscous timescale. Some trends are actually seen in accreting neutron star systems, but then the increase in the period corresponds to the decrease in the overall emissivity, which is in opposite direction than the trend discussed here. However, if the future instrumental time resolution and the photon count rate allow to see the evolution of a period during a single QPO episode, the expected correlations is likely to apply for such case.

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